(2)

MTL TR 89-33

AD

AN INVESTIGATION OF THE WORKABILITY OF Al-8.5% Mg ALLOYS

MARIETTA R. CAPPUCCI
METALS RESEARCH BRANCH

April 1989

Approved for public release; distribution unlimited.

US ARMY
LABORATORY COMMAND
MATERIALS TECHNOLOGY LABORATORY

U.S. ARMY MATERIALS TECHNOLOGY LABORATORY
Watertown, Massachusetts 02172-0001

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER MTL TR 89-33	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) AN INVESTIGATION OF THE WORKABILITY OF Al-8.5% Mg ALLOYS		5. TYPE OF REPORT & PERIOD COVERED Final Report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Marietta R. Cappucci		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Materials Technology Laboratory Watertown, Massachusetts 02172-0001 SLCMT-EMM		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS D/A Project: 1L162105.AH84
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Laboratory Command 2800 Powder Mill Road Adelphi, Maryland 20783-1145		12. REPORT DATE April 1989 13. NUMBER OF PAGES 13
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Aluminum alloys, Lightweight alloys, High strength alloys, Rolling (metallurgy), Microstructure

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(SEE REVERSE SIDE)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

Block No. 20

ABSTRACT

Aluminum-magnesium alloys containing greater than 5 wt% magnesium are high strength, lightweight alloys which show potential to be utilized by the Army in armor applications. A problem encountered thus far with these high strength alloys is some difficulty in achieving necessary cold work levels to provide the alloys with optimum mechanical properties. This report details the results of an investigation of the hot and cold workability of three Al-8.5 wt% Mg alloys with variations in Mn and Cr additions.

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

INTRODUCTION

The need for lighter weight, higher strength armor alloys has been recognized by the Army for several years. These alloys would reduce the weight of a hull structure and allow vehicles to travel at faster speeds, travel further, or carry more armament than their counterparts, while expending the same amount of energy.[1]

Strain-hardenable aluminum-magnesium alloys have been used in the majority of aluminum military vehicles to date. These 5xxx series alloys provide the advantages listed above and show a low susceptibility to stress-corrosion cracking (SCC).[2-4] Conventional aluminum-magnesium alloys in use are 5083, containing 4.45 wt% Mg, and 5456, containing 5.25 wt% Mg. Both the tensile and fatigue strength increase, and density decreases as the magnesium content of an alloy is raised.[5] Increasing the magnesium content to values still higher than those of 5083 and 5456 will potentially result in alloys with higher strengths and lighter weights than the currently utilized alloys. CS-19, an aluminum alloy with 7.75 to 8.75 wt% Mg has exhibited yield strength and fracture toughness values superior to those of 5456 as well as showing improved resistance to SCC.[6] Further development of aluminum alloys with higher percentages of magnesium would therefore enable the Army to meet the goal of producing a lighter weight, higher strength armor alloy.

The problem encountered with these high magnesium alloys is that it is difficult to achieve the levels of cold work necessary to obtain optimum properties, due to surface cracking and plate alligatoring as a result of inhomogeneous deformation during rolling.[7]

The alloys under investigation in this study are Al-8.5 wt% Mg alloys with manganese and chromium added for strength and grain size control. This report details the results of an investigation of the workability of these alloys. Possible explanations and solutions to the responses to hot and cold working are proposed.

EXPERIMENTAL PROCEDURE

Thermo-Mechanical Processing

Three alloys, A, B, and C, of varying composition (Table 1), were supplied by Reynolds Metals Co., as 22-pound ingots.

Table 1. COMPOSITION OF Al-Mg ALLOYS (WT%)

Alloy	Al	Mg	Mn	Cr	Fe	Si
A	Bal	8.83	0.55	0.00	0.02	0.004
B	Bal	8.64	0.00	0.11	0.01	0.000
C	Bal	8.38	0.56	0.12	0.02	0.020

1. VAN HORN, K., ed. Aluminum. Vol. 2. American Society for Metals, Metals Park, Ohio, 1967, p. 455-466.
2. CONSERVA, M., and LEONI, ı. *Effect of Thermal and Thermo-Mechanical Processing on the Properties of Al-Mg Alloys.* Met. Trans. A., v. 6A, 1975, p. 189-195.
3. SPROWLS, D. *High Strength Alumium Alloys With Improved Resistance to Corrosion and Stress-Corrosion Cracking.* Tri-Service Conference on Corrosion, MCIC-77-33, Battelle Columbus Laboratory, 1976, p. 89-120.
4. BEBERDICK, L. *Naval Post Graduate School Report.* no. AD-A110 563/4, 1981.
5. VAN HORN, K., ed. *Aluminum, Vol. 1.* American Society for Metals, Metals Park, Ohio, 1967, p. 167, 313.
6. ROGERS, R. W., VERNAM, W. D., and SHUMAKER, M. *Test and Exploratory Development of an Optimum Aluminum Alloy System for Ship Structures.* Aluminum Company of America, Contract No. N00024-72-C-5571, 1974.
7. SCHEY, J. A. *Fracture in Rolling Processes.* J. Applied Metalworking, v. 1, 1980, p. 48-59.

The ingots were machined to workable dimensions of 3.5" x 3.5" x 7" and solution heat treated at a temperature of 725^{0}F for 2 hours, followed by rapid quenching in an ice-water bath. The alloys were then forged at 810^{0}F to 2"-square bars. The forgings were allowed to equilibrate to 675^{0}F. The alloys were hot rolled at this temperature to a thickness of 1.25" in three equal passes, followed by further reduction to 1.005" in four additional passes, with heating between passes to maintain the temperature. The rolling was performed at a strain rate of 1.2 s^{-1}.

Cold rolling of the alloys was then planned according to the following schedule: seven passes, each pass reducing the plate by 0.05", to a final thickness of 0.65"; a total reduction during cold rolling of 35%.

Microstructural Analysis

The microstructures of alloys A, B, and C were characterized through the use of optical and scanning electron microscopy, as well as the use of an energy dispersive X-ray spectrometer (EDS). Optical microscopy was utilized to reveal grain structure and size, as well as constituent particle size and concentration. The specimens were polished through 1 μm diamond paste and the surfaces of both the prerolled and rolled specimens were then etched with Keller's etchant for microstructural observation.

A scanning electron microscope (SEM) was used to study the fracture surface of the samples which failed during processing. EDS was used to identify particles which were possible initiators of fracture.

EXPERIMENTAL RESULTS

Of the three solution treated alloys, B and C were successfully forged at 810^{0}F. However, edge cracks developed in the specimen of composition A in the process of forging.

Hot rolling was carried out according to the aforementioned schedule. Upon completion of the hot rolling process, it was observed that alloys B and C rolled without any indication of plate cracking. Edge and central cracks were again present throughout alloy A, possibly as a result of both through-thickness and lateral inhomogeneities.[7]

The three alloys were subsequently cold worked. All of the alloys were successfully rolled to 25% reduction (five passes). In the sixth pass, alloy A alligatored. Alloy C completed the sixth pass but alligatored during the seventh pass. In both cases, the splitting crack propagated throughout almost the entire length of the plate (Figure 1). Alloy B was rolled to a thickness of 0.70" (a 30% reduction), without any indication of edge cracking.

HRB values were measured for each of the alloys in the as-cast, solution treated, and rolled condition. It is clear from the values indicated in Table 2 that alloy C, containing both manganese and chromium, is slightly harder than alloy A and is markedly harder than alloy B. After rolling the hardness of each of the alloys increases, retaining the same general hardness relationships that existed prior to rolling. Alloy B shows the greatest response to work hardening, with hardness values increasing by 57%, as opposed to 33% and 30% for alloys A and C, respectively.

Table 2. HRB VALUES OF AS-CAST, SOLUTION TREATED, AND ROLLED ALLOYS

Alloy	As-Cast	Solution Treated	Rolled
A	50.3	47.8	63.5
B	39.8	39.5	62.4
C	51.2	50.6	66.0

Microstructural Characterization

Figure 2 illustrates the microstructure of alloy B in the solution heat treated (unrolled) condition. In alloy B, the chromium-containing alloy, limited grain-boundary precipitation is observed. Elongated, 13-μm particles are present along the grain boundaries, and spherical particles 9 μm in diameter are present in the matrix. These particles contain large amounts of iron and chromium (Figure 3), the iron originating as an impurity in the initial casting.

In contrast to the microstructure observed in alloy B, alloy C retained its dendritic structure after the 2-hour heat treatment (Figure 4). The concentration of matrix and grain-boundary particles is much higher than that in alloy B. Acicular, 25 μm intermetallics are present in both the matrix and along the grain boundaries of the alloy, while spherical particles 6 μm in diameter are present in the matrix. SEM characterization was performed on alloy C to identify the composition of these particles. As can be seen in Figure 5, the intermetallics are $(FeMn)Al_6$, with some chromium present. Alloy A also has a relatively high concentration (Figure 6) of high manganese-containing particles (Figure 7).

The solution treated alloys exhibited a relatively equiaxed grain structure. A composite micrograph of the structure of alloy C, after rolling, is illustrated in Figure 8. A summary of grain size, determined by the Heyn intercept method[8] for the solution treated and rolled alloys, is presented in Table 3.

Table 3. GRAIN DIMENSIONS OF SOLUTION TREATED AND ROLLED ALLOYS

Alloy	Solution Treated Alloys Grain Size (μm)	Rolled Alloys Grain Size (μm)		
		LT	ST	RD
A	175			
B	171	38.8	7.0	127
C	563			

Figure 9 shows SEM micrographs of the alligatored surface of alloy C. The fracture mechanism is by microvoid initiation, growth, and coalescence, and both dimples and cleavage facets are observed. The dimples in these fracture surfaces were initiated at an interface between the matrix and inclusions. The size of the dimples varies greatly depending upon the size and concentration of the initiating particles. An analysis of one such particle, marked E in Figure 10, is illustrated in Figure 11. As is shown in Figure 11, the composition of the particle in the dimple is identical to that of the particle analyzed in Figure 5.

8. ABRAMS, H. *Grain Size Measurement by the Intercept Method.* Metallography, v. 4, 1971, p. 59-78.

DISCUSSION

The alligatoring phenomenon is a defect which is most likely the result of an inhomogeneity in the deformation process, in combination with the processing of a material with an inherently low ductility.

The rolling was performed with a low h/L ratio (the ratio of the ingot height to the length of the projected arc of contact). At low h/L ratios, deformation is severe in the center of the billet. The rolling results in a tensile stress normal to the rolling plane,[9] and in the early stages of rolling, defects and cracks are initiated. Upon further rolling, the stresses generated would cause an opening up along these already weakened areas,[10] therefore resulting in an alligatored plate.

Alloy B, Al-Mg-Cr, did not alligator. Because the deformation conditions were identical for all three alloys, the secondary tensile stresses developed due to inhomogeneous deformation should have been equivalent; it follows that this chromium-containing alloy has a higher ductility than the alloys containing manganese. This conclusion has been confirmed by Lloyd[11] and shall be further discussed in the following section.

In comparing the microstructures of the manganese-containing alloys to that containing just chromium, it was shown that alloy C had a larger grain size than alloy B resulting in more inhomogeneous deformation. In addition, it is also apparent that there is a difference in constituent particle distribution. Alloy C contains larger, and more numerous particles than alloy B. It has been shown that solution heat treatment and heating schedules will affect the ductility and the particle distribution.[12] In a study of the deformation of Al-Mg alloys, Lloyd[11] has concluded that deformation and fracture are significantly influenced by the constituent particles. During deformation, instabilities grow rapidly, and voiding at constituent particles enhances this instability growth. Therefore, the alloys with the fewer number of particles have the greater tensile ductility. This supports the observation that alloy B, the alloy with a lower particle concentration, had a higher ductility and did not alligator.

SUMMARY AND CONCLUSIONS

1. Upon rolling the Al-8.5% Mg alloys, through-thickness and lateral inhomogeneities led to the development of secondary tensile stresses that resulted in initiation and propagation of cracks and defects in the material.

2. Alloy B, the alloy with the lower particle concentration, was the more ductile alloy due to the decreased presence of sites for void initiation followed by fracture by microvoid coalescence.

3. The majority of the particles present were identified to contain the tramp element iron, along with the secondary alloying element.

9. MEADOWS and PEARSON. *Discussion.* J. Inst. Metals, v. 92, 1964, p. 254-256.
10. POLAKOWSKI, N. H. *An Examination of Modern Theories of Rolling in the Light of Rolling Mill Practice.* J. Inst. Metals, v. 76, 1950, p. 754-757.
11. LLOYD, D. J. *The Deformation of Commercial Al-Mg Alloys.* Met. Trans. A., v. 11A, 1980, p. 1287-1294.
12. LEE, S-L., and WU, S-T. *Influence of Soaking Treatments on Hot Ductility of Al-4.85 Percent Mg Alloys Containing Mn.* Met. Trans. A., v. 17A, 1986, p. 833-841.

4. Alloys A and C, the manganese-containing alloys, had a higher concentration of particles than did the chromium-containing alloy B, indicating a higher potential for fracture by the mechanism of microvoid coalescence.

5. The inhomogeneity of the rolling process, combined with the inherently low ductility of the Al-8.5% Mg-Mn alloys, result in the alligatoring of some of these alloys.

RECOMMENDATIONS

1. Reduce the amount of the iron impurity present in the original casting.

2. Develop an optimum heat treatment which solutionizes as many of the detrimental precipitates as possible, thereby reducing the number of sites for initiation of fracture.

3. Perform both hot and cold rolling of the low ductility alloys at lower strain rates.

4. Conduct mechanical property tests to determine tensile strengths and ductilities of the alloys both before and after the rolling process.

Figure 1. Alloy C— alligatored plate.

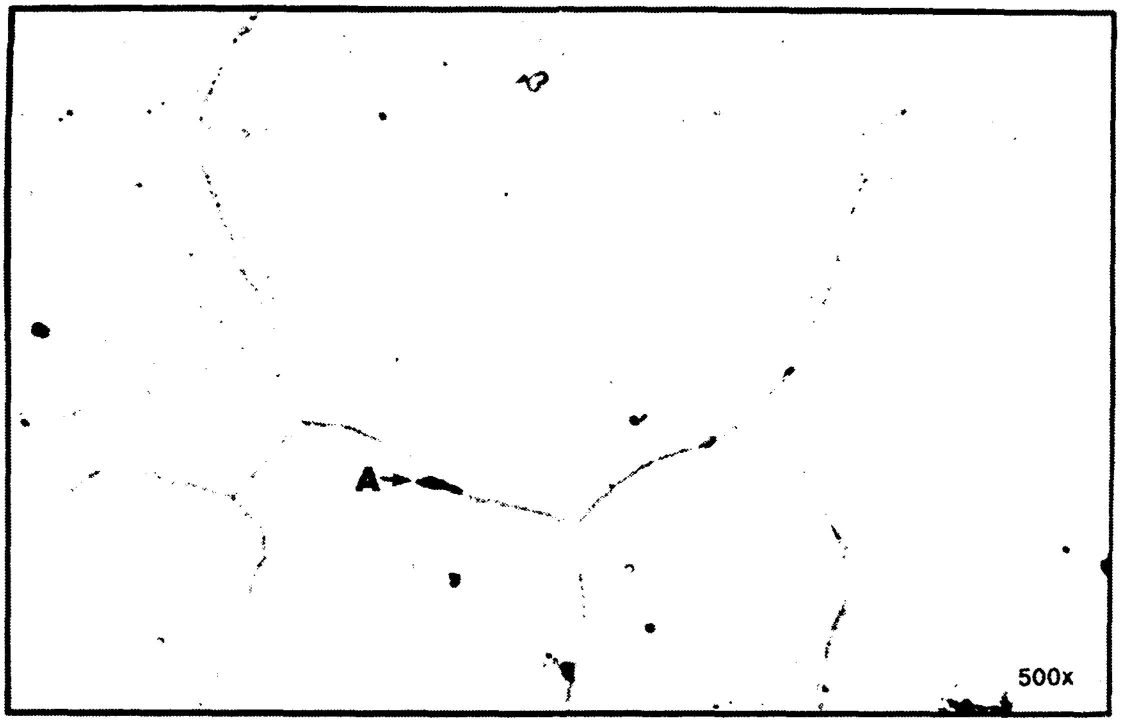


Figure 2. Microstructure of alloy B.

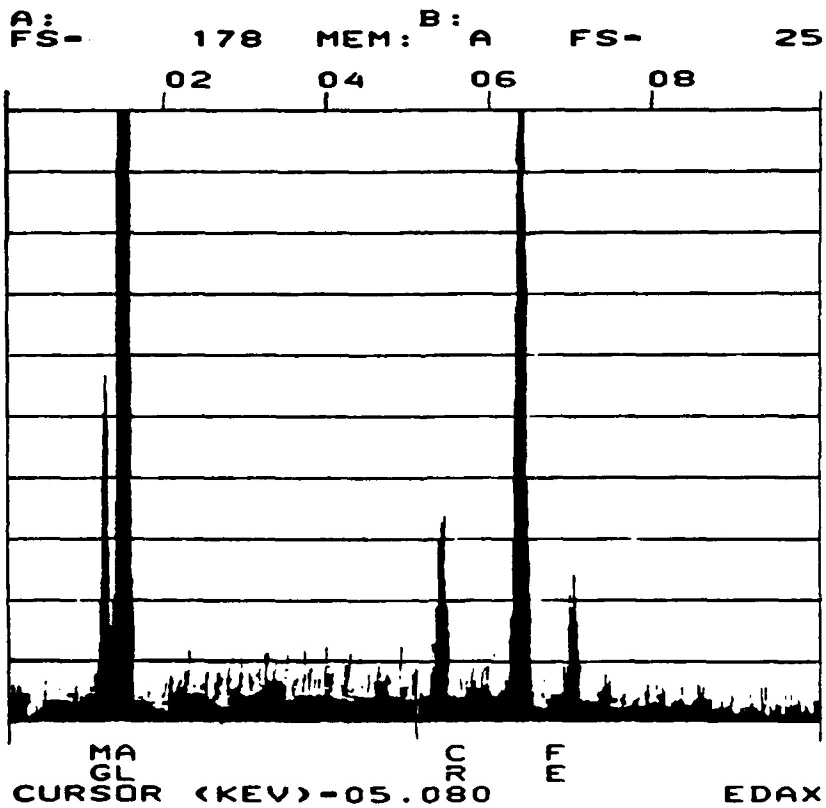


Figure 3. EDS of particle A of Figure 2.

Figure 4. Microstructure of alloy C.

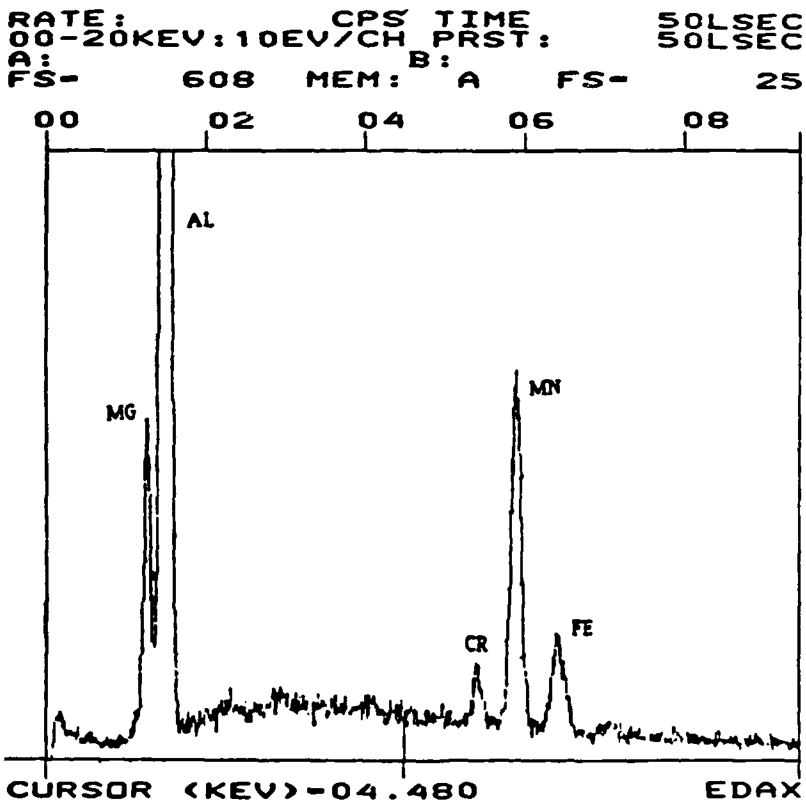


Figure 5. EDS of particle B of Figure 4.

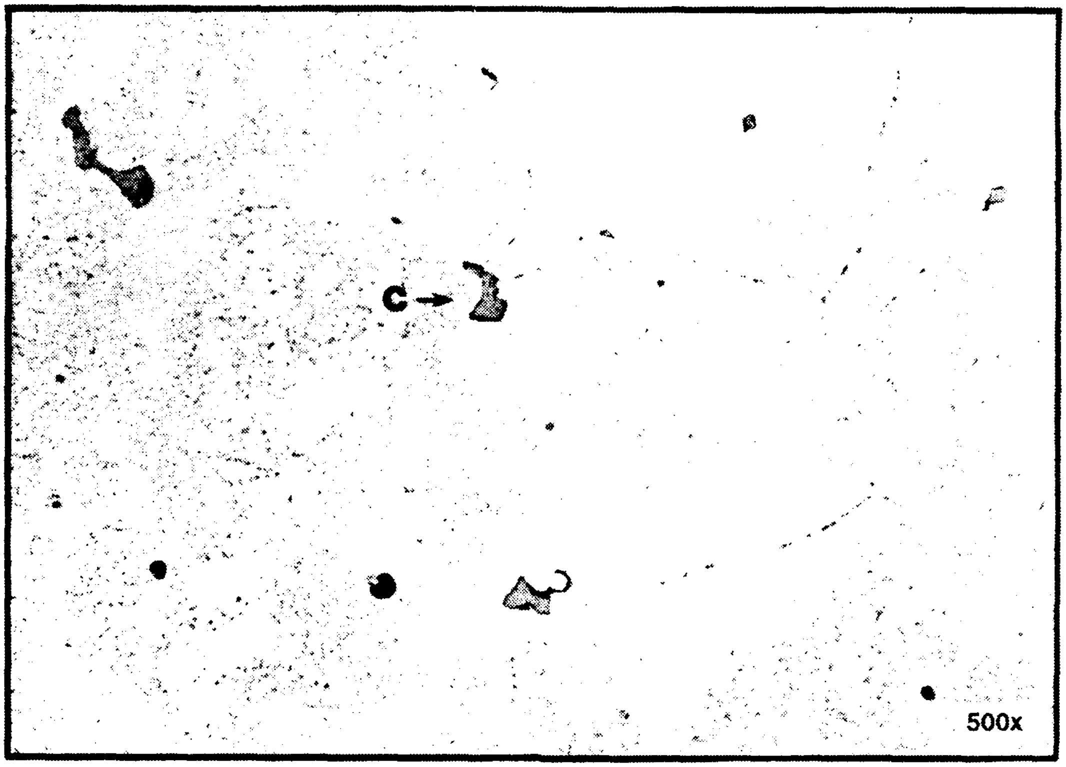


Figure 6. Microstructure of alloy A.

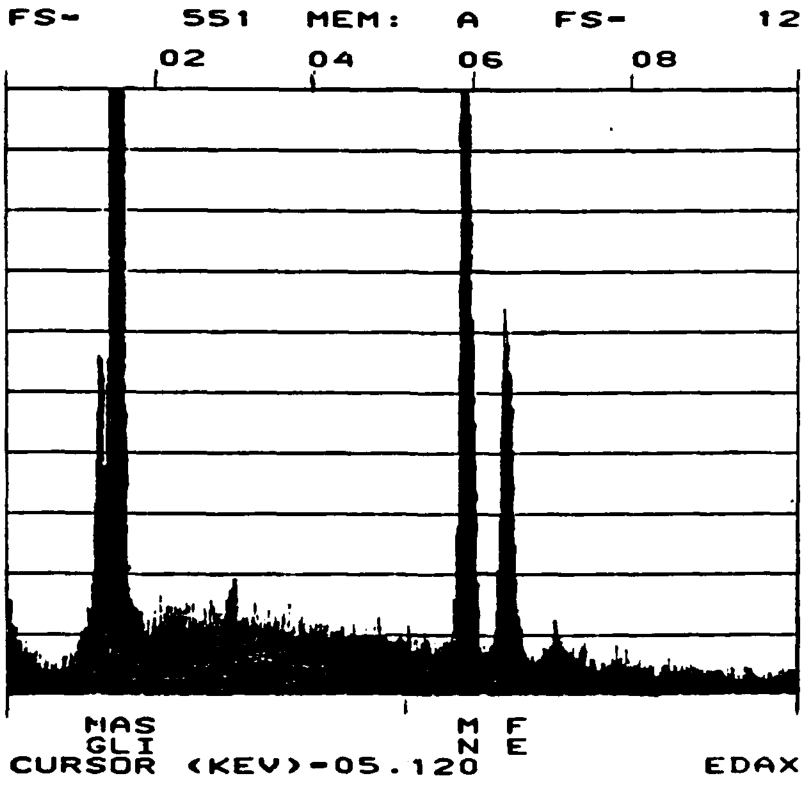


Figure 7. EDS of particle C of Figure 6.

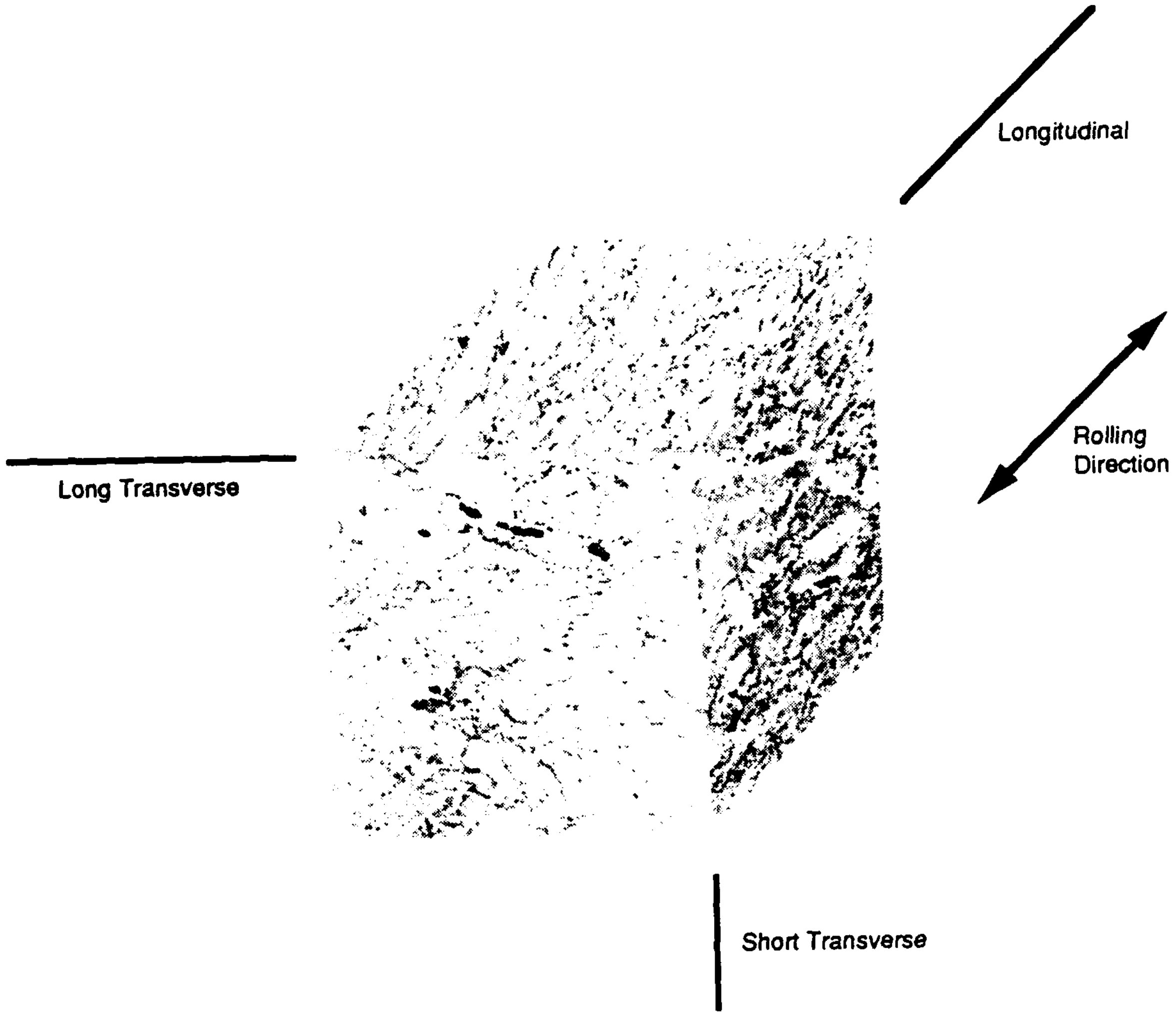
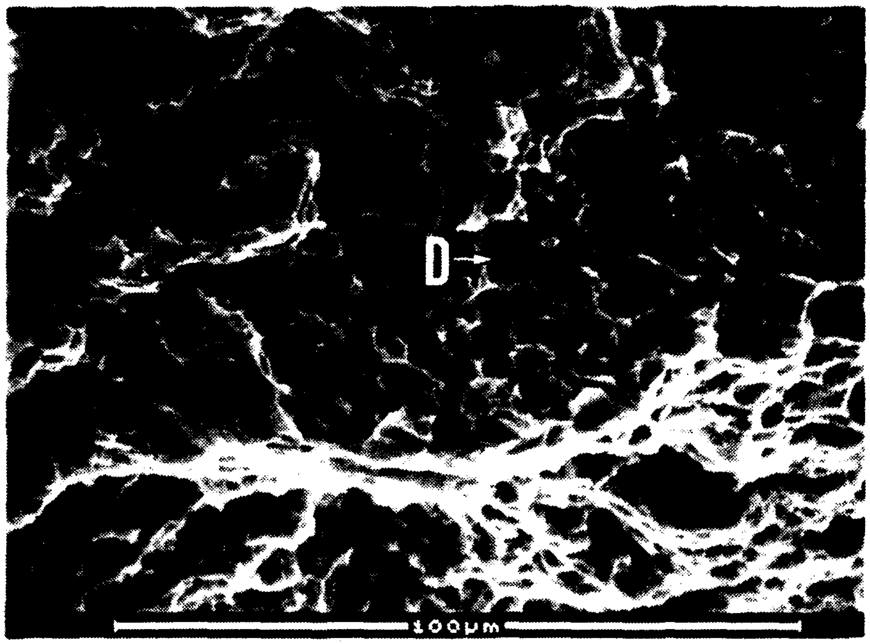
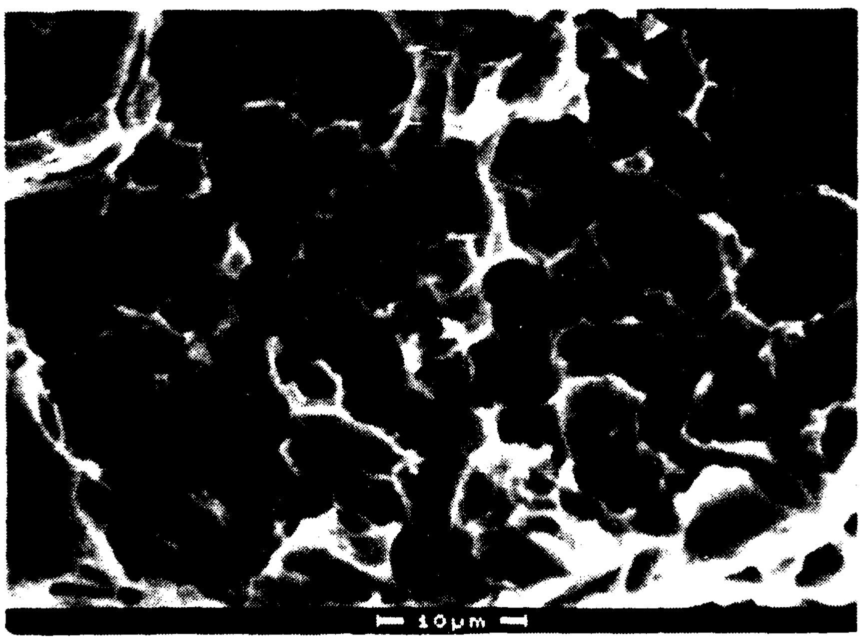


Figure 8. Composite micrograph of rolled alloy C.



(a) Fractograph of Alligatored Surface



(b) Enlarged View of Particle D of (a)

Figure 9. SEM micrographs of the alligatored surface of alloy C.

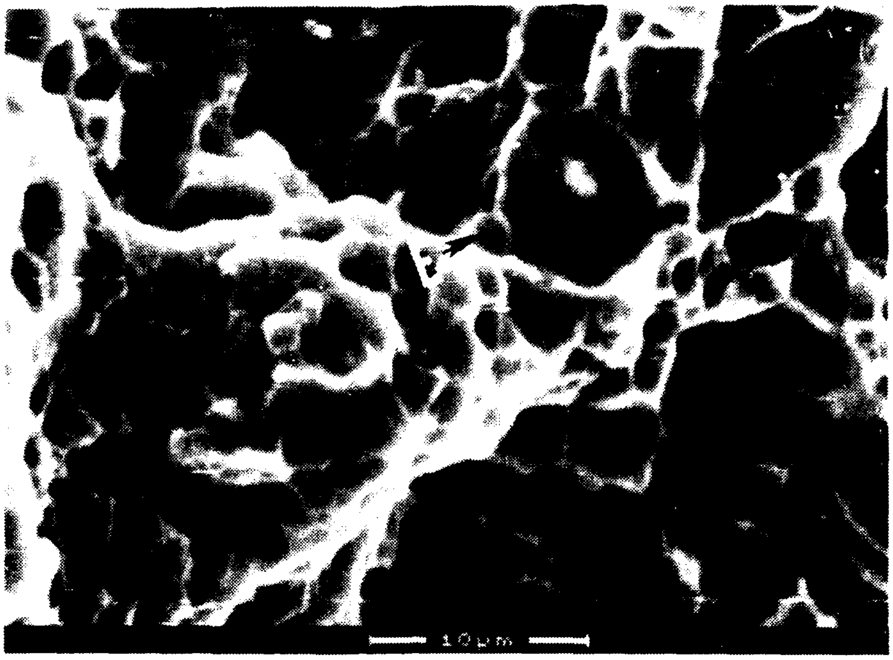


Figure 10. Fractograph of alligatored surface of alloy C.

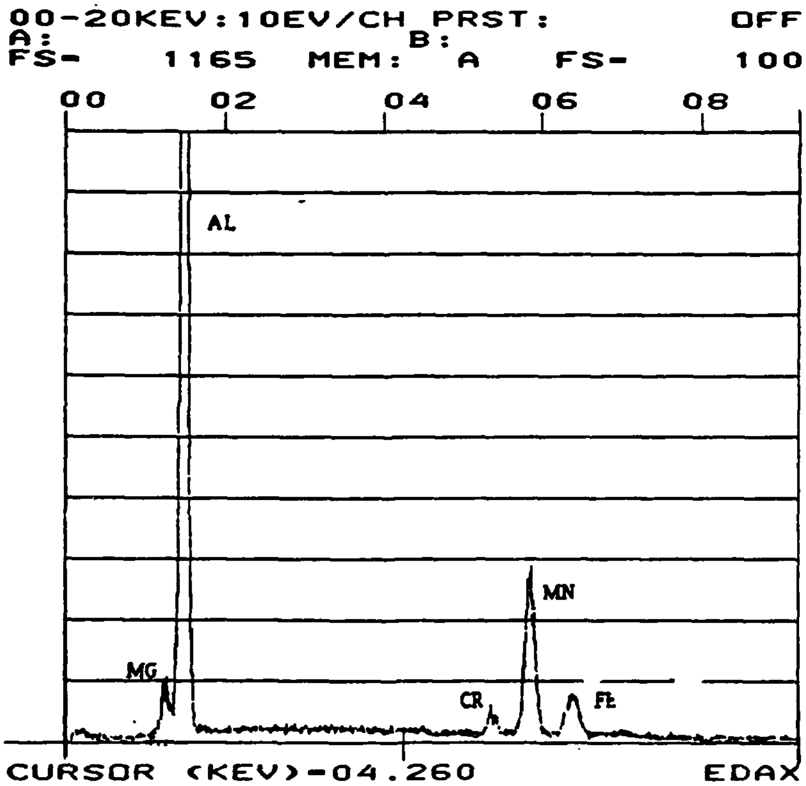


Figure 11. EDS of particle E of Figure 10.

DISTRIBUTION LIST

No. of Copies	To
1	Office of the Under Secretary of Defense for Research and Engineering, The Pentagon, Washington, DC 20301
	Commander, U.S. Army Laboratory Command, 2800 Powder Mill Road, Adelphi, MD 20783-1145
1	ATTN: AMSLC-IM-TL
	Commander, Defense Technical Information Center, Cameron Station, Building 5, 5010 Duke Street, Alexandria, VA 22304-6145
2	ATTN: DTIC-FDAC
	Metals and Ceramics Information Center, Battelle Columbus Laboratories, 505 King Avenue, Columbus, OH 43201
1	ATTN: Harold Mindlin
	Commander, Army Research Office, P.O. Box 12211, Research Triangle Park, NC 27709-2211
1	ATTN: Information Processing Office
	Commander, U.S. Army Materiel Command (AMC), 5001 Eisenhower Avenue, Alexandria, VA 22333
1	ATTN: AMCLD
	Commander, U.S. Army Materiel Systems Analysis Activity, Aberdeen Proving Ground, MD 21005
1	ATTN: AMXSY-MP, Director
	Commander, U.S. Army Missile Command, Redstone Scientific Information Center, Redstone Arsenal, AL 35898-5241
1	ATTN: AMSMI-RD-CS-R/Doc
1	AMSMI-CS, R. B. Clem
	Commander, U.S. Army Armament, Munitions and Chemical Command, Dover, NJ 07801
2	ATTN: Technical Library
	Commander, U.S. Army Tank-Automotive Command, Warren, MI 48397-5000
1	ATTN: AMSTA-ZSK
2	AMSTA-TSL, Technical Library
1	AMSTA-RCK
	Commander, U.S. Army Foreign Science and Technology Center, 220 7th Street, N.E., Charlottesville, VA 22901
1	ATTN: Military Tech
	Director, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, VA 23604-5577
1	ATTN: SAVDL-E-MOS (AVSCOM)
1	SAVDL-EU-TAP
	U.S. Army Aviation Training Library, Fort Rucker, AL 36360
1	ATTN: Building 5906--5907
	Commander, U.S. Army Aviation Systems Command, 4300 Goodfellow Boulevard, St. Louis, MO 63120-1798
1	ATTN: AMSAV-GTD
1	AMSAV-E
1	AMCPEO-AV
	Naval Research Laboratory, Washington, DC 20375
1	ATTN: Code 5830
1	Code 2627
	Chief of Naval Research, Arlington, VA 22217
1	ATTN: Code 471
	Director, Structural Mechanics Research, Office of Naval Research, 800 North Quincy Street, Arlington, VA 22203
1	ATTN: Dr. M. Perrone

No. of Copies	To
	Commander, U.S. Army Aeromedical Research Unit, P.O. Box 577, Fort Rucker, AL 36360
1	ATTN: Technical Library
	Commander, U.S. Army Agency for Aviation Safety, Fort Rucker, AL 36362
1	ATTN: Technical Library
	Commander, USACDC Air Defense Agency, Fort Bliss, TX 79916
1	ATTN: Technical Library
	Commander, U.S. Army Engineer School, Fort Belvoir, VA 22060
1	ATTN: Library
	Commander, U.S. Army Engineer Waterways Experiment Station, P. O. Box 631, Vicksburg, MS 39180
1	ATTN: Research Center Library
	Commandant, U.S. Army Quartermaster School, Fort Lee, VA 23801
1	ATTN: Quartermaster School Library
1	Edward J. Morrissey, AFWAL/MLTE, Wright-Patterson Air Force, Base, OH 45433
	Commander, U.S. Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, OH 45433
1	ATTN: AFWAL/MLC
1	AFWAL/MLLP, M. Forney, Jr.
1	AFWAL/MLBC, Mr. Stanley Schulman
	National Aeronautics and Space Administration, Marshall Space Flight Center, Huntsville, AL 35812
1	ATTN: R. J. Schwinghammer, EH01, Dir, M&P Lab
1	Mr. W. A. Wilson, EH41, Bldg. 4612
1	Committee on Marine Structures, Marine Board, National Research Council, 2101 Constitution Ave., N.W., Washington, DC 20418
1	Librarian, Materials Sciences Corporation, Guynedd Plaza 11, Bethlehem Pike, Spring House, PA 19477
	Wyman-Gordon Company, Worcester, MA 01601
1	ATTN: Technical Library
	Lockheed-Georgia Company, 86 South Cobb Drive, Marietta, GA 30063
1	ATTN: Materials and Processes Engineering Dept. 71-11, Zone 54
	General Dynamics, Convair Aerospace Division, P.O. Box 748, Fort Worth, TX 76101
1	ATTN: Mfg. Engineering Technical Library
1	Mr. R. J. Zentner, EAI Corporation, 626 Towne Center Drive, Suite 205, Joppatowne, MD 21085-4440
	Director, U.S. Army Materials Technology Laboratory, Watertown, MA 02172-0001
2	ATTN: SLCMT-TML
1	Author

U.S. Army Materials Technology Laboratory
Watertown, Massachusetts 02172-0001
AN INVESTIGATION OF THE WORKABILITY OF
Al-8.5% Mg ALLOYS - Marietta R. Cappucci

AD____________
UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Technical Report MTL TR 89-33, April 1989, 13 pp-
illus-tables, D/A Project: 1L162105.AH84

Aluminum alloys
Lightweight alloys
High strength alloys

Aluminum-magnesium alloys containing greater than 5 wt% magnesium are high strength, lightweight alloys which show potential to be utilized by the Army in armor applications. A problem encountered thus far with these high strength alloys is some difficulty in achieving necessary cold work levels to provide the alloys with optimum mechanical properties. This report details the results of an investigation of the hot and cold workability of three Al-8.5 wt% Mg alloys with variations in Mn and Cr additions.

U.S. Army Materials Technology Laboratory
Watertown, Massachusetts 02172-0001
AN INVESTIGATION OF THE WORKABILITY OF
Al-8.5% Mg ALLOYS - Marietta R. Cappucci

AD____________
UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Technical Report MTL TR 89-33, April 1989, 13 pp-
illus-tables, D/A Project: 1L162105.AH84

Aluminum alloys
Lightweight alloys
High strength alloys

Aluminum-magnesium alloys containing greater than 5 wt% magnesium are high strength, lightweight alloys which show potential to be utilized by the Army in armor applications. A problem encountered thus far with these high strength alloys is some difficulty in achieving necessary cold work levels to provide the alloys with optimum mechanical properties. This report details the results of an investigation of the hot and cold workability of three Al-8.5 wt% Mg alloys with variations in Mn and Cr additions.

U.S. Army Materials Technology Laboratory
Watertown, Massachusetts 02172-0001
AN INVESTIGATION OF THE WORKABILITY OF
Al-8.5% Mg ALLOYS - Marietta R. Cappucci

AD____________
UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Technical Report MTL TR 89-33, April 1989, 13 pp-
illus-tables, D/A Project: 1L162105.AH84

Aluminum alloys
Lightweight alloys
High strength alloys

Aluminum-magnesium alloys containing greater than 5 wt% magnesium are high strength, lightweight alloys which show potential to be utilized by the Army in armor applications. A problem encountered thus far with these high strength alloys is some difficulty in achieving necessary cold work levels to provide the alloys with optimum mechanical properties. This report details the results of an investigation of the hot and cold workability of three Al-8.5 wt% Mg alloys with variations in Mn and Cr additions.

U.S. Army Materials Technology Laboratory
Watertown, Massachusetts 02172-0001
AN INVESTIGATION OF THE WORKABILITY OF
Al-8.5% Mg ALLOYS - Marietta R. Cappucci

AD____________
UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Technical Report MTL TR 89-33, April 1989, 13 pp-
illus-tables, D/A Project: 1L162105.AH84

Aluminum alloys
Lightweight alloys
High strength alloys

Aluminum-magnesium alloys containing greater than 5 wt% magnesium are high strength, lightweight alloys which show potential to be utilized by the Army in armor applications. A problem encountered thus far with these high strength alloys is some difficulty in achieving necessary cold work levels to provide the alloys with optimum mechanical properties. This report details the results of an investigation of the hot and cold workability of three Al-8.5 wt% Mg alloys with variations in Mn and Cr additions.